A statistical model for brain networks inferred from large-scale electrophysiological signals

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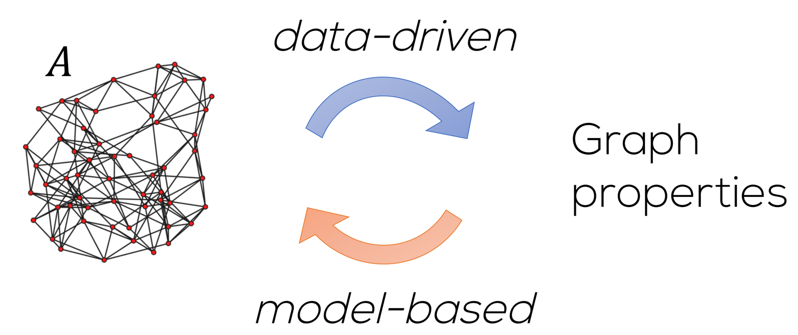
Network science has been extensively developed to characterize structural properties of brain networks. As a result of the inference process, networks, estimated from experimentally obtained biological data, represent one instance of a large number of realizations with similar intrinsic topology [1].

A modelling approach is therefore needed to support statistical inference.

In this work we adopted a statistical model based on exponential random graph (ERGM) to reproduce electroencephalographic (EEG) brain networks [3].

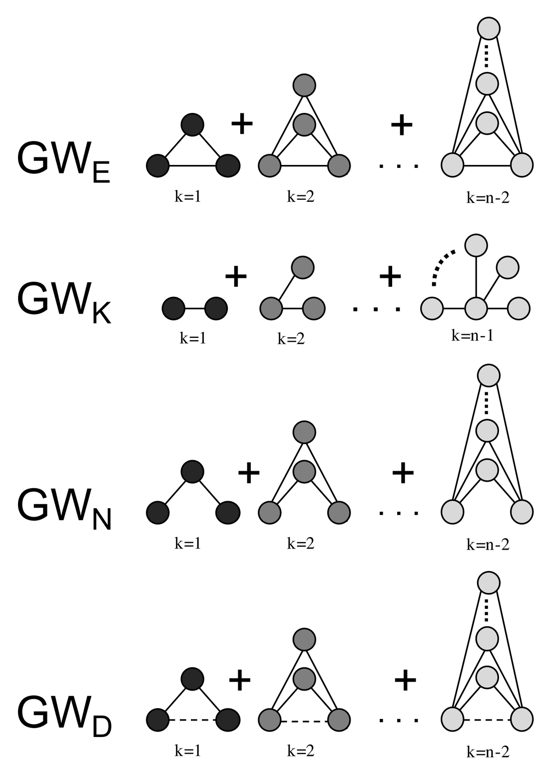


Methods

Exponential Random Graph Models (ERGMs) [2,4]

General form: $P(A) = \frac{\exp\{\sum_i \theta_i\, g_i(A)\}}{z(\theta,\mathcal{A})}$

Conditional: $\frac{P(A_{ij}=1)}{P(A_{-ij},\boldsymbol{\theta})} = \frac{1}{[1+exp\{-\boldsymbol{\theta}'\Delta_{ij}(\boldsymbol{g}(A))\}]}$



Data

We validated this approach in a dataset of **N = 108 healthy subjects during eyes-open (EO) and eyes-closed (EC) resting-state conditions** [5]. We constructed brain networks estimated from high-density EEG signals. Nodes are the electrodes and links are computed using **spectral coherence** which quantifies the level of synchrony between two stationary signals at a specific frequency band.

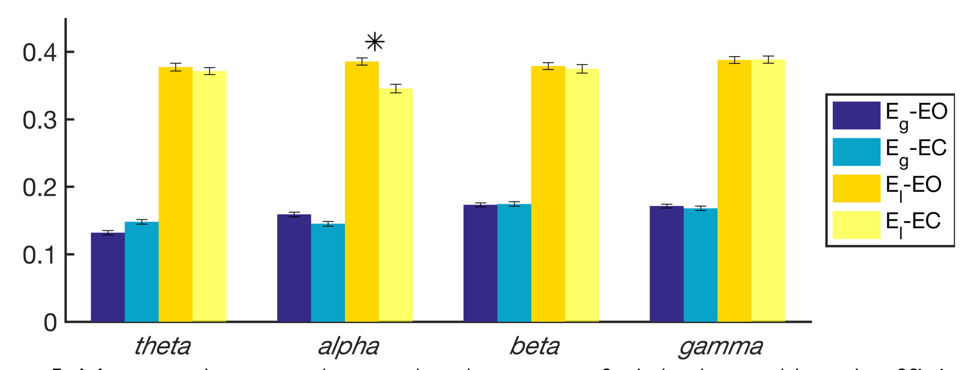


Figure 1: Mean values and standard errors of global- and local-efficiency measured from EEG brain networks. *p-value < 0.001.

Results

We tested different configuration models and ranked them according to a score based on the **integration and segregation properties** of networks

$$\delta(E_g, E_l) = max(|\eta_{E_g}|, |\eta_{E_l}|)$$

models	edges	GW_K	GW_E	GW_N	GW_D
M_1	*	✓	✓	–	—
M_2	*	—	✓	—	✓
M_3	*	—	—	✓	✓
M_4	*	—	✓	✓	—
M_5	*	—	✓	—	—
M_6	*	—	—	✓	—
M_7	*	✓	—	✓	—
M_8	*	✓	—	—	✓
M_9	*	✓	—	—	—
M_{10}	*	—	—	—	✓
M_{11}	✓	—	✓	✓	—

Table 1: Set of model configurations.

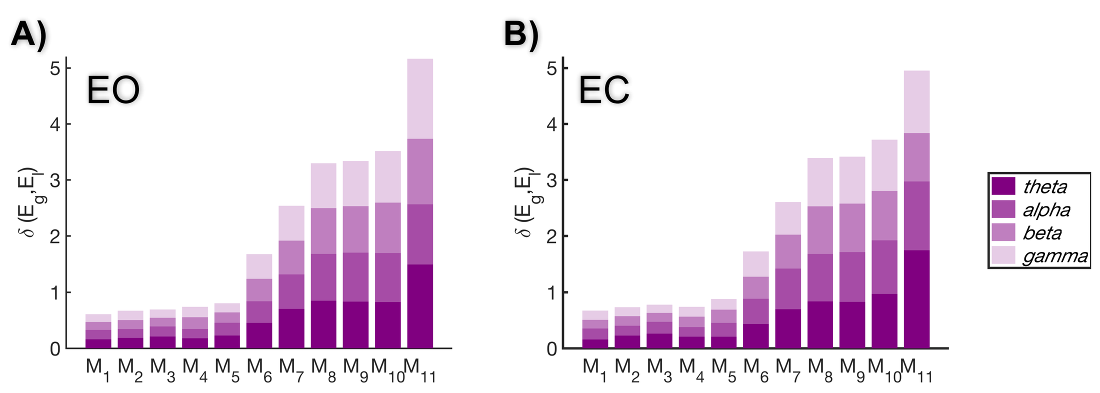


Figure 2: Absolute quality of the fit of ERGMs.

M_1 ranked first showing that **triangles and stars** are fundamental constituents of functional brain networks.

We assessed the goodness-of-fit of the model M_1, cross-validate the results by means of other graph metrics (Figure 3) and performed a statistical group analysis.

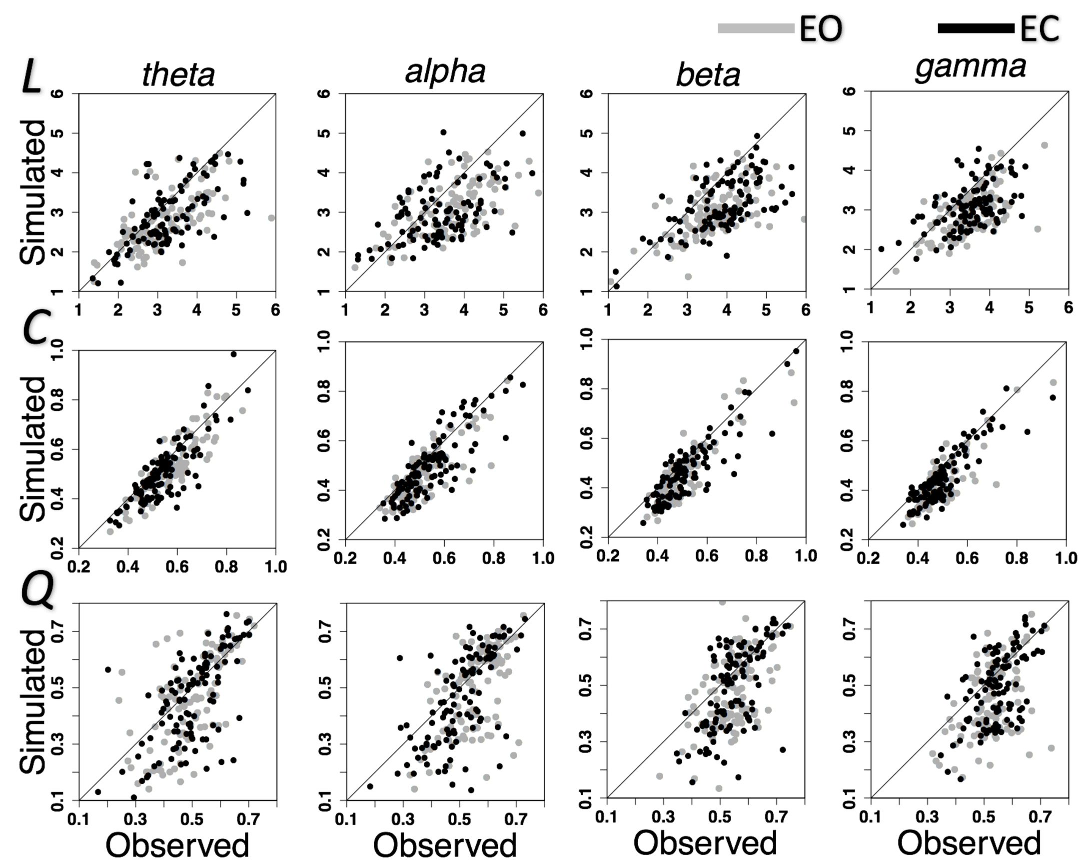


Figure 3: Scatter plots show the values of the graph indices, characteristic path length (*L*), clustering coefficient (*C*) and modularity (*Q*), measured in the observed brain networks (x-axis) against the mean values obtained from synthetic networks (y-axis).

The group analysis over the synthetic networks revealed the ability of M_1 to capture not only the individual properties of brain networks but also the main observed difference between EO and EC resting states, i.e. the **increase in the local efficiency from EC to EO** in the *alpha* band.

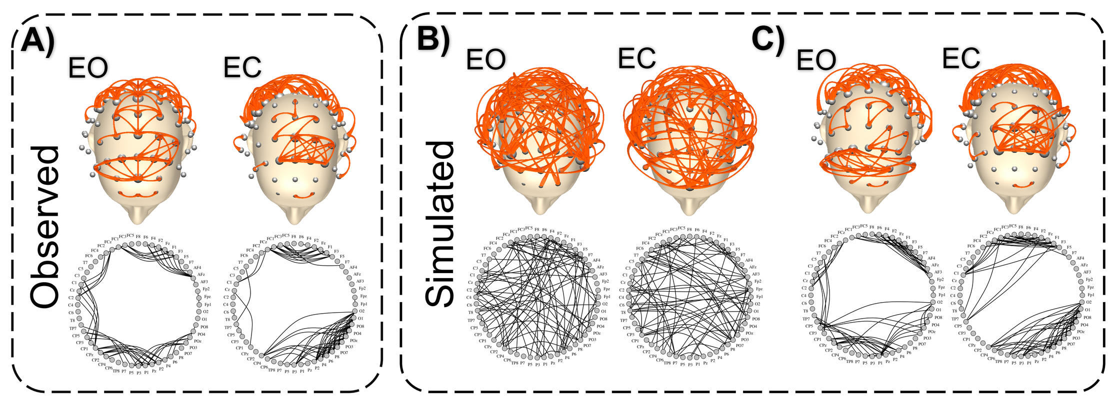


Figure 4: A) Brain network in the *alpha* band for EO and EC resting-state. B) One instance of the corresponding synthetic networks generated by the model. C) Because node labels are not preserved in the simulated networks, we re-assigned them virtually by using the Frank-Wolfe algorithm. In the upper part of the figure, nodes correspond to EEG electrodes. In the bottom part, the nodes are arranged into a circle.

	θ_1			θ_2		
	EO	EC	EO − EC	EO	EC	EO − EC
theta	1.528 (0.045)	1.531 (0.039)	−0.281 (0.7804)	1.502 (0.169)	1.443 (0.159)	−0.406 (0.690)
alpha	1.449 (0.041)	1.297 (0.039)	3.746 (0.0002)	1.327 (0.123)	1.317 (0.532)	−1.084 (0.347)
beta	1.487 (0.457)	1.326 (0.046)	1.514 (0.0009)	1.062 (0.149)	1.303 (0.169)	−0.890 (0.371)
gamma	1.552 (0.046)	1.509 (8.266)	−0.992 (0.8521)	0.878 (0.125)	1.140 (3.002)	−1.064 (0.135)

Table 2: Median values (and standard errors) are reported for EO and EC resting-state conditions. T-values (and p-values) from non-parametric permutation-based t-tests between EO and EC are shown in the third column of each subsection marked with the heading EO-EC.

By inspecting the ERGM we see that positive $\boldsymbol{\theta_1} > \mathbf{1}$ and $\boldsymbol{\theta_1} > \mathbf{1}$ values indicates that both GW_E and GW_K are fundamental connectivity features that emerge in brain networks more than expected by chance.

However, only θ_1 values showed a significant difference (EO > EC) in the *alpha* band, as well as in the *beta* band, suggesting that the tendency to form triangles, rather than the tendency to form stars, is a discriminating feature of EO and EC modes.

Conclusions

In this work we adopted a statistical model based on exponential random graph (ERGM) to reproduce electroencephalographic (EEG) brain networks. The results showed that the tendency to form triangles (GW_E) and stars (GW_K) was sufficient to statistically reproduce the main properties of the EEG brain networks, such as functional integration and segregation.

References

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